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Smartphone sensing and identification of shock noise and vibration induced by gym activities

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Featured Application: The new findings highlight for the first time the application of smartphone sensors to determine and identify shock noise and vibration induced by gym activities. It also demonstrates a real case study that can be applicable to end users of the gym facilities. The method in the article can be used (not limited to) as a reference for identifying excessive noise and vibration that can be harmful to human.

Abstract: Fitness culture has significantly grown since the 19th century. In the recent decade, the gym and fitness industry has thrived in many countries. The construction of gymnasiums has increased dramatically, and fitness centres have become one of the most common spaces in mix-used buildings around the world. There are a significant number of gyms located relatively close to residential areas, some of which have even proposed to operate 24 hours a day. The noise and vibration generated by dropping free weights in the gym affects the user experience and the surrounding community to a certain extent. In addition, gyms todays are frequently operated out of refurbished retail units. Most refurbished unit buildings' structures were never designed to host a gym, which makes the mitigation of noise and vibration very difficult. Based on critical literature reviews, the use of gymnasiums flooring system is relatively straightforward to mitigate the noise and vibration but its effectiveness is hardly monitored. This study mainly discusses the use of material for mitigating noise and vibration in the gymnasiums together with the crowd-sensing evaluation of vibration effectiveness, uncertainty, materials deterioration to manage appropriate level of noise and vibration. The gym at the University of Birmingham has been chosen as a case study. Over 10 hours of field tests have been conducted to record data of the operating floor material in the gym and fitness centre using novel smartphone sensors. Considering the specific floor material, a strategy of reducing noise and vibration is proposed. In addition, health and safety assessments are also carried out to evaluate the public safety condition in the gym. The insight into novel crowdsourcing smartphone sensors can help end users to real time monitor the environmental impacts around the gyms and surroundings.

Keywords: impact noise; shock; vibration; gym; gym-induced noise; crowdsourcing sensor; smartphone.

1. Introduction

The 2018 State of the UK Fitness Industry Report [1] shows that the UK health and fitness industry continues to grow. The UK has more gyms, more users and a greater market share than ever before. The report stresses that there are more than 7,000 gyms in the UK for the first time, total membership or users is approaching 10 million and market value is just under £5 billion. The data shows that the market penetration rate remains at 14.9%, so 1 in every 7 people in the UK is a member of a gym. This implies that the construction of fitness centres has increased dramatically, and fitness centres have become one of the most common spaces in mix-used buildings around the world [2-4]. In fact, a significant number of gyms are located relatively close to or even within the residential areas, some of which have even proposed for 24/7 operations. This has raised a concern whether the rapid gym establishment is sufficient and sustainable to the public and the users when considering environmental noise and vibrations. In contrast, the study into shock noise and vibration induced by gym activities is relatively limited. On this ground, it is necessary to identify the issues in order to build knowledge and capacity in dealing with shock and vibration induced by gym activities.

Dropping heavy weight of objects is indispensable for the operation of a gym. The dropping weight could be down to a small light weighted dumbbell or up to the heavy loaded barbell. The induced impact noise and vibration cause a different level of negative influence to the gym surrounding areas. This could be damage to the building structure (e.g. ceiling, pipeline, floor, etc.), threat to user health safety (hearing loss, dementia, etc.), decrease equipment's durability or even mental influence (e.g. temper, panic, etc.). Although there are a large number of open literatures published about mitigating N&V in general, the research about strategy of reducing N&V in particular commercial gym environment is extremely limited and inadequate [4-10]. Therefore, a detailed study on the noise and vibration induced by gym activities is necessary and is highly valuable. The emphasis of this study is placed on the Sport & Fitness Centre at the University of Birmingham. The venue has been recently built for less than 2 years and the conditions of gym equipment and infrastructure are relatively new (as shown in Figure 1). Completed test data, noise example, and test arrangements can be found in the Appendices (provided as a supplimentay material).

Figure 1. General conditions of gym space at the University of Birmingham.

Figure 2. Noise transmission model.

The aim of this study is to identify and minimize the influence of noise and vibration to the gym building by using novel smartphone sensors to monitor the concern. The case study of Sport & Fitness Centre at the University of Birmingham has been chosen to demonstrate the issues. This paper presents the application of the noise and vibration theory into the gym environment noise control assessment, in order to evaluate the effectiveness of floor rubber in suppressing N&V in the gym; to evaluate the deterioration of floor materials; and to develop a strategy for mitigating N&V specifically based on the fitness centre at the University of Birmingham, UK. The case study has been emphasized to highlight the importance of the issue and to provide a practical guideline for N&V mitigations. The demonstration of smartphone sensors can be used for real-time monitoring of the environment impacts by end users in the future.

2. Literature review

2.1 Noise uncertainty

In the gym environment, there are various source of noise such as drop of dumbbells, training machines, treadmills, music, regular bus passing nearby etc. [4-9]. There are continuous and intermittent sound within the environment and makes the measurement of ambient noise becomes relatively inaccurate. Möser [10] proposed the most conventional and simplest method is the so-called "energy-equivalent continuous sound level" L_{eq}:

$$L_{eq} = 10\log\left(\frac{1}{T}\int_0^T \frac{p^2\,(t)}{p_0^2}\right)dt = 10\log\,(\frac{1}{T}\int_0^T 10^{L(t)/10})dt \quad (1)$$

where $p_0 = 20 \times 10^{-6}\,Pa$,

$p\ \ (t)$ is the instantaneous sound pressure,

$L(t) = 10\log\,(p\ \ (t)/p_0)^2$ is the level gradient over time

This method could enhance the ambient noise data analysis statistically in the further field data collection of this research [10]. The mean values could be used to determine or verify the maximum permissible noise levels in the Gym at the University of Birmingham.

2.2 Effectiveness of materials

2.2.1 Selection of material

The choice of materials has been designed considering cost, carbon footprint and deterioration of material [11]. PULLUM was consulted by The University of Birmingham Sport & Fitness centre in order to customize flooring system and platforms. This case study is conducted by considering PULLUM's material specification.

2.2.2 Industrial Case

A case study was presented based on the initial acoustic assessment of a commercial Fitness centre – "Fitness Bot Pty Ltd". The fitness centre is located at within a mixed-use development building at 235 Homebush Road, Strathfield, New South Wales. According to the assessment, the noise and vibration are most likely to decrease within the following categories [12]:

- Vibration transmission – where vibration generated within the training studio is transmitted throughout the building structure and into adjacent tenancies;
- Regenerated noise – where noise is produced within the adjacent areas of the building, resulting from the transmission of vibration throughout the building structure; and
- Airborne noise transmission – where noise within the training studio is transmitted through wall partitions into the adjacent occupancies.

The assessment provided the regenerated noise emission and structural vibration as the two main data collections. A Class 1 sound level meter (SLM) and a high sensitivity tri-axial geophone with vibration data logger were used to measure the noise and vibration data respectively. 7 combinations of various floor materials were set as test sample [12]. A free weight of 15kg dumbbell was set as a maximum dropped weight from the height of 150mm to simulate free fall dropping from user's chest level. According to the results, the optimal combination sample in the test can be tabulated in Table 1.

Table 1. Recommended Floor Systems – All free Weights areas [12].

Option	Finished Floor Topping	Energy Absorbing Layer
1	8mm thick Regupol Everroll rubber gym floor topping	2 layers of 40mm thick Regupol^{TM} 4080 impact isolation underlay (density 200 kg/m^3)
2	8mm thick Regupol Everroll rubber gym floor topping	75mm thick Regupol^{TM} FX75 impact isolation underlay

By comparing the optimal combination to the one without any energy-absorbing rubber matting, the regenerated noise could be decreased by approximately 5-6 dB. For vibration, the values could be decreased by between 2 dB and 10 dB depending on the test scenario and parameters [12]. In conclusion, although this assessment focussed on the influence of noise and vibration on the residential spaces located above the gym and aimed to achieve Australian standards, the research in this report can be enhanced in the following ways:

- The data-collecting equipment could be changed to meet industry standards.
- Doubling the energy-absorbing rubber matting was not as efficient as expected.
- The vibration calculation results should be calculated for worst-case scenarios.
- The selection of material should also take into account product quality, durability, warranty and manufacturer's installation specifications.

2.3 Laboratory and in-situ tests

There were a few studies related to testing the influence of gym and sports noise. Masoumi et al.'s report [13] argued that gyms are becoming more and more common in the UK, and gyms are frequently located in refurbished retail units. Most refurbished building structures were never designed to host a gym. Therefore, the construction of a new concrete slab or increasing the unit's height is not feasible; therefore, a lightweight flooring system may be necessary. In their report, Masoumi et al. [13] tested the performance of a floor system with various configurations, such as damping layers, various thicknesses of an air void, floor coverings and bending stiffness. The test data were plotted as a graph to analyse the transmission loss and frequency. The flooring system diagrams, configurations [12, 13]. To sum up, the report investigated several related characteristics:

- Lightweight and heavy weight flooring system provide similar manifestation.
- Lightweight floors can handle higher vibrational frequency ranges if the stiffness and damping configurations are well adjusted.
- The mixture of floor and damping layers have a major influence on final performance.
- At lower frequencies range, floor finishing is not adequate for mitigating structure-borne noise.

3. Methodology

3.1 Evaluation of critical problems

In general, impact noise and vibration will most likely appear at the source, which means that the majority of vibration is generated when a dropped weight makes contact with the flooring. Therefore, the proposed meaningful data collection will focus on this critical area. Note that the vibro-acoustics of lower floors are not within the scope of this study.

3.2 Instrument consideration

3.2.1 Use of instrument

According to the international standard IEC 61672-1 and British standard BSEN 61672, sound-level meters, integrating-averaging sound-level meters and integrating sound-level meters are the most common sound-measuring instruments. In the data collection portion of this research, the proposed measuring instruments were chosen to conform as much as possible to the standards. In addition, the measuring equipment used in the industrial case study mentioned in section 2.5 can be used as a reference [12] for the initial consideration.

3.2.2 Selection of measuring instrument

According to a previous study, contemporary smartphones can be potentially used as a sound-level meter or even as a dosimeter [13]. The majority of contemporary smartphones have built-in sensors, such as microphones, GPS, accelerometers, cameras, light sensors, gyroscopes, etc., that enable them to be used in this way. In addition, Kardous and Shaw [14] noted that 'several government and research organisations have commissioned participatory noise pollution monitoring studies using mobile phones.

Smartphone application developers provide various product across the Apple iOS and Android platforms. By leveraging smartphones and software, a more informative result can be generated compared to conventional sound-testing instruments. The majority of free applications at least provide basic sound-test results including the minimum, maximum and average values in dB. In addition to that, some advanced applications can also provide a real-time noise graph, geographical location information, temperature measuring or even calibration functions. These functions can complement each other to provide more comprehensive results. Furthermore, the majority of the sound-testing applications are relatively more user-friendly than conventional meters. However, it is important to note that to the sampling frequency of accelerometers built in smartphones (currently limited to 100 Hz) is not enough to cover the frequency range of interest for the structural borne noise (e.g. at 200-250 Hz). Mobilephone sensors are generally suitable to vibro-acoustic measurements at low frequencies.

3.2.3 Instrument specifications

According to a detailed report by Murphy and King [15], various tests can be done to investigate the metering accuracy of different smartphone brands on the market by varying models, operation system platforms, testing environments and apps. The release date of the tested smartphone was between 2010 and 2014. The report concluded that the Apple iOS generally provides more precise results than Android platform apps, especially when recording ambient background noise. Although one of the test results showed that HTC smartphone could provide relatively good performance, it will be neglected from the list of potential smartphone-based noise and vibration tools because the test sample was too small.

In addition, Murphy and King [15] report also mentioned that there could be a significant difference between using a smartphone and a tablet for noise testing. Roberts [16] stated that the location of microphones on tablets is more varied than on smartphones. This is because the majority of tablets are not designed for phone calls, a factor that could affect the consistency of data collection when using a tablet.

To sum up these specification concerns, the measuring instruments should be chosen from iPhones from similar production years. The model should be as consistent as possible. The selected iPhone models are listed in Table B1 (Appendix B provided in the supplimentay material). All the devices have been checked by measuring the same sound signal (55 dB) produced by 'Decibel X'. The distance between each device and the sound source is set to be 1 m equally. Some variations can be found to be around 1 dB, which is acceptable.

3.2.4 Selection of applications

There are various free applications for noise and vibration metering on the App Store platform. Each has specific features, so it is necessary to compare and select a suitable one for the desired test. The specifications of free, mainstream sound and vibration metering apps in the market are listed and compared in Table 2 below:

Table 2. Sound meter application features.

Name	Developer	Basic sound test	Max & Min value	Geographical data	Real time graph	Temperature	Calibration	Precise data (1 d.p.)	Comment
dB Meter	Vlad Polyanskiy	✔	✔		✔		✔		Provide good interface but data is not sufficient precise
Decibel Meter	Ashraf Thoppukadavil	✔	✔						Provide relative high refreshing rate but not sufficient precise data
Decibel X	SkyPaw Co. Ltd	✔	✔	✔	✔	✔	✔	✔	Overall provide sufficient and relative precise information
NIOSH SLM	EA LAB	✔	✔				✔	✔	Provide detailed data but lack of graphical output
Sound meter	LQH Apps	✔	✔		✔			✔	Graphical output scale is too small and cannot be adjusted
Spectrum	Elena Polyanskaya	✔	✔		✔				Great graphical output but not sufficient precise data

According to these features, Decibel X is the best fit for the desired test. It is user-friendly and provides comprehensive information. Most importantly, it can generate graphs of noise over time, which can be used to analyse the influence of the surrounding noise and ensure that the targeted activity is recorded correctly. Therefore, Decibel X was selected as the main noise-testing application as shown in Table 3.

Overall, none of the free applications in the mainstream market provide comprehensive information for the desired vibration test. Nevertheless, based on a number of calibrations with accelerometers, *Accelerometer and Sensors Lite* relatively provides the most precise data set (with the least standard deviation) among the tested apps. In addition, 'Accelerometer App' (available on iOS and Android) is capable of outputting three-axis vector data for further analysis, such as importing into MATLAB for generating a detailed graph. This feature could supplement the apps' inadequate graph adjustment capabilities. Therefore, Accelerometer Apps has been selected to test vibration. Although a recent work [17] showed that more validation with class 1 sound level meter is desirable, our comparison with accelerometer measurements shows that the precision of the data set obtained from the Apps is reliable so that an adjustment can be done at a later stage to understand the trend of the results. Appendix B (in the supplimentay material) shows the calibrations of mobile sensors with conventional measurements.

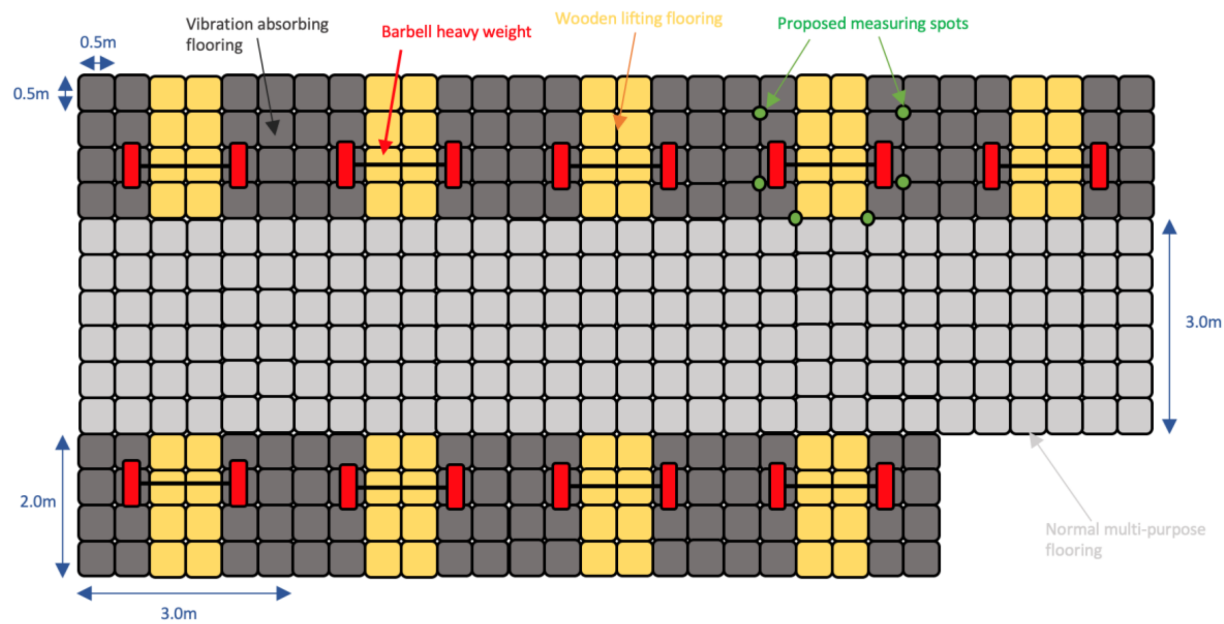
Table 3. Vibration meter application features

Name	Developer	Numerical data	Average value	Adjustable graph scale	Real time graph	3-axis vibration data	Raw data export	Precise data (3 d.p.)	Comment
Accelerometer	DreamArc	✔			✔	✔	✔	✔	High refreshing rate and precision. Original data could be exported.
Sensors Lite	Philip Broder	✔			✔	✔		✔	High precision with up to 6 d.p. but free version doesn't provide recording function.
Smart Vibration Meter	NETIGEN Kluzowicz	✔	✔		✔				Only provide 1 d.p. recording data.
Vibration analysis	Dmitriy Kharutskiy			✔	✔			✔	Graph scale could be adjusted but without numerical data.
VibrationMeter	Andrew Neal	✔	✔	✔	✔				Provide good graph interface but only with 1 d.p. data
Vibrometer	ExaMonile S.A.	✔	✔	✔	✔				Provided data is not sufficient precise (1 d.p.)

3.3 Data collection plan

3.3.1 Measurement plan and assumptions

A simple initial field survey was done for generating a rough floor plan of the free-weight lifting area at the University of Birmingham Sport & Fitness Centre (more details are in Appendix A in the supplimentay material).



a) sketch of heavy weight lifting area floor plan

b) floor plan view

c) floor material

d) Lifting area

Figure 3. Heavy weight lifting environment

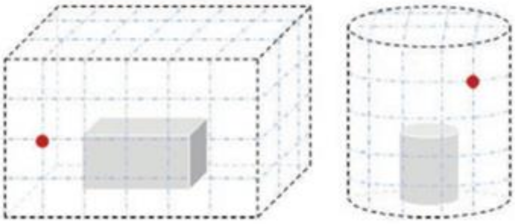


Figure 4. Measurement surfaces with measurement points indicate by grid lines

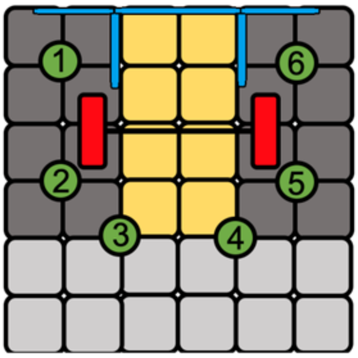


Figure 5. Sketch of proposed test area floor

Fig 3 shows the environment of heavy lifting floor in the gym. Each lifting area is approximately 2 m × 3 m with two different floor finishings. The green dots indicate the proposed sound-level meter location. According to ISO 9614-1, the distance interval between every meter should be greater than 0.5 m. ISO 9614-1 method was chosen because the conditions under which it can be accomplished are less restrictive than those in the ISO 3740 methods.

Fig 4, provided by SIEMENS [18], demonstrates a model for operators to place the sound-level meters around a source, which can yield a sound power contour. Fig 5 shows an enlarged version of the test area floor plan. The numbers indicate the test device positions (more details in Table B1 of Appendix B provided in the supplimentay material). The position of devices should remain constant between every set of tests to maintain consistency. The blue lines in Fig 5 indicate the barbell rig's location in the lifting area, which can also be used to store substituted weight plates. Two field tests have been conducted (more details in Appendix A provided in the supplimentay material). The total weight of the rig can be over 320 kg depending on the weight plate usage rate. The additional influence of the barbell rig on the reducing vibration aspect will be discussed in a later section.

By referring to the environmental noise survey of Sandilands's Edgbaston central campus development plan [5], there are several methodologies can be reviewed when applying a similar concept to this research. Fig 6, provided by Sandilands [5], shows the various noise survey locations surround a gym building.

The various testing locations represent different group of object:

- MP1 represents residential properties.
- MP2 represents the university's lodge.
- MP3 represents the closest windows to the site.
- MP4 represents the nearest offices.

To account for 24 hrs a day operations, the development plan also tested the noise data in various time slots and ensured it was under the restricted limit. Similarly, the data collection in this study should be spread out to various spots in the gym to measure different conditions. In addition, peak time and off-peak time data should be separated for analysis.

Figure 6. Environmental noise survey plan [5]

Figure 7. Upright position [19]

Figure 8. Finishing position [19]

3.3.2 Barbell weight lifting exercise analysis

By several informal peak-time field surveys in the University of Birmingham Sport & Fitness Centre, the most common exercises in the barbell weight-lifting area are the squat, stiff-leg deadlift, bent-over rows and upright rows. Figs 7 and 8, provided by Gardner [19], shows the upright and finishing position of a stiff leg deadlift, respectively. The maximum distance of the weights from the floor material must be determined and kept constant in every set of tests.

Due to the difference in the targeted muscle groups, the barbell squat and stiff-leg barbell deadlift could involve heavier weights among the exercises. In addition, all the exercises mentioned above could involve the use of barbell rests on the training frame except for the stiff-leg deadlift. These factors mean the stiff-leg barbell deadlift should be considered as the most likely exercise in which heavy weights would be accidentally or purposely dropped in the fitness centre.

Although Olympic weightlifting exercises could involve dropping the weight to the floor from a higher position, the usage rate of this exercise is relatively low in a normal gym. Therefore, the stiff-leg barbell deadlift was selected as the main test exercise.

3.3.3 Testing procedures

Because the desired testing area is communal and cannot be reserved, the testing time was chosen such that there are as few users as possible. Every single weight dropped during stiff-leg barbell deadlifts would be recorded when following the measuring requirements mentioned in section 4.3.1. The main test took various aspects into consideration, such as investigating the relationship between dropped weights and noise and vibration, uncertainty, the influence of the barbell weight plates' material, the effectiveness of the floor material and material deterioration.

In Table 4, 13 combinations of various weight plates are listed in increasing total weight with an interval of 5 kg. Note that the weight is lifted 100 mm of drop height. The combinations C through K were selected to achieve the aim of increasing weight without changing the contact area between the weight plate and the floor material. Sample test photo shown in Appendix A (in the supplimentay material). The combinations of L and M were selected to investigate and compare the effect of different materials of corresponding weights.

Table 4 – Main combinations of various weight plate

	Combination	**Weight (kg)**
A	Barbell (15kg) + 2x2.5kg metal plate	20.0
B	Barbell (15kg) + 2x5.0kg metal plate	25.0
C	Barbell (15kg) + 2x10kg rubber covered plate	35.0
D	Barbell (15kg) + 2x10kg rubber covered plate + 2x2.5kg metal plate	40.0
E	Barbell (15kg) + 2x10kg rubber covered plate + 2x5.0kg metal plate	45.0
F	Barbell (15kg) + 2x10kg rubber covered plate + 2x5.0kg metal plate + 2x2.5kg metal plate	50.0
G	Barbell (15kg) + 2x10kg rubber covered plate + 4x5.0kg metal plate	55.0
H	Barbell (15kg) + 2x10kg rubber covered plate + 4x5.0kg metal plate + 2x2.5kg metal plate	60.0
I	Barbell (15kg) + 2x10kg rubber covered plate + 6x5.0kg metal plate	65.0
J	Barbell (15kg) + 2x10kg rubber covered plate + 6x5.0kg metal plate + 2x2.5kg metal plate	70.0
K	Barbell (15kg) + 2x10kg rubber covered plate + 8x5.0kg metal plate	75.0

L	Barbell (15kg) + 2x2.5kg Plastic Bumper plate	20.0
M	Barbell (15kg) + 2x5.0kg Plastic Bumper plate	25.0

Because the experiment can only be carried out in an uncontrollable environment, the influence of other users is unavoidable, especially during the vibration test. Therefore, the test should be carried out with as many sets as possible to estimate a valid average value to analyse. Four sets of both the noise and vibration tests were conducted, and average values were calculated by considering the recorded data from all six devices. In addition, in order to minimise the error in the vibration tests, three-axis data were recorded and carried out to the maximum magnitude.

4. Results

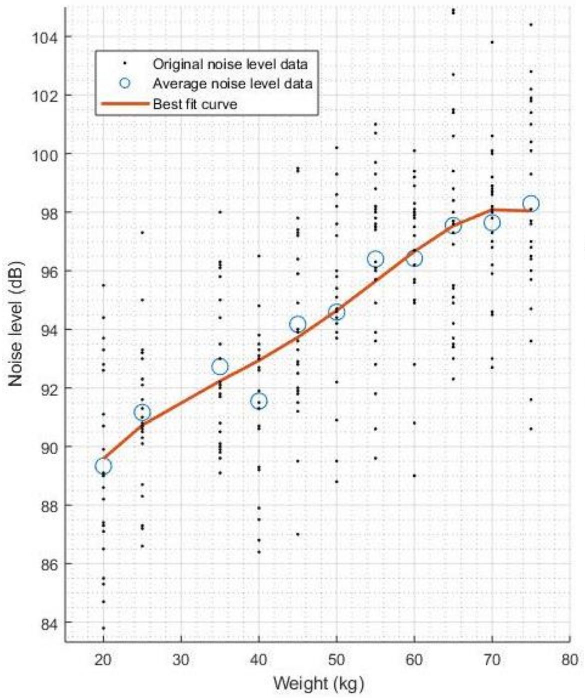
The collected test data are recorded in Table 5 form for further calculation purposes. A summarised averaged value table for both the noise and vibration tests is shown below.

Table 5. Representative data of noise and vibration tests of the main combinations

		Noise					Vibration				
		Average set data				Finial average	Average set data				Finial average
Combination	Weight (kg)	Set 1	Set 2	Set 3	Set 4	Noise level (dB)	Set 1	Set 2	Set 3	Set 4	Vibration level (m/s^2)
A	20.0	89.0	89.0	88.3	91.0	89.3	0.087	0.214	0.148	0.156	0.151
B	25.0	90.0	91.9	90.6	92.2	91.2	0.242	0.312	0.140	0.156	0.213
C	35.0	91.4	92.5	91.8	95.2	92.7	0.231	0.290	0.244	0.204	0.242
D	40.0	91.9	91.1	91.6	91.6	91.6	0.232	0.169	0.533	0.207	0.285
E	45.0	92.3	93.8	95.9	94.7	94.2	0.484	0.152	0.198	0.220	0.263
F	50.0	93.7	94.5	95.4	94.8	94.6	0.158	0.225	0.621	0.325	0.332
G	55.0	95.0	96.1	97.1	97.5	96.4	0.435	0.278	0.401	0.190	0.326
H	60.0	95.4	97.1	97.7	95.5	96.4	0.414	0.582	0.308	0.667	0.493
I	65.0	95.9	99.8	96.8	97.7	97.5	0.540	0.370	0.447	0.588	0.486
J	70.0	97.2	98.2	99.2	96.0	97.6	0.309	0.590	0.404	0.601	0.476
K	75.0	99.6	98.8	96.8	98.0	98.3	0.897	0.442	0.619	0.672	0.658
L	20.0	98.8	96.0	99.2	96.8	97.7	0.170	0.176	0.258	0.257	0.215
M	25.0	98.4	97.6	95.4	100.2	97.9	0.198	0.344	0.286	0.266	0.273

The complete overall data and original three-axis vibration test data are listed in Tables A1 and A2 (Appendix A in the supplimentay material), respectively.

By setting the maximum damage factor as 0.5, the allowance of lifetime traffic volume could be solved through equations 3 and 4.



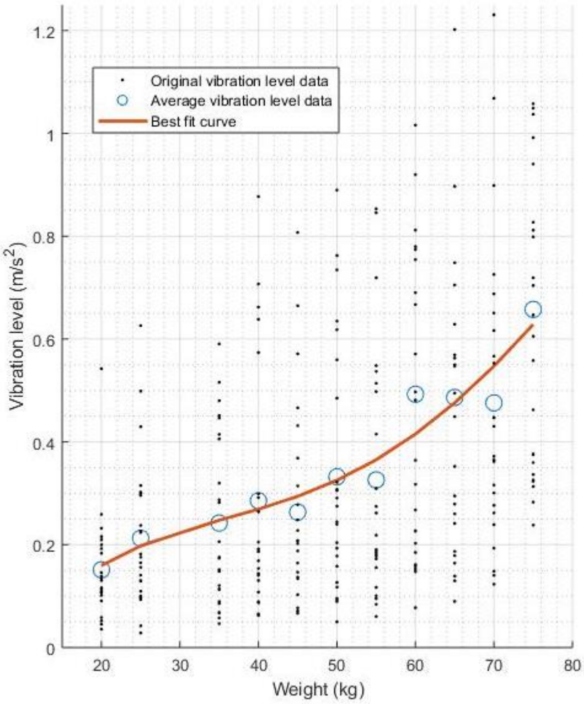


Figure 9. Noise versus drop weight graph

Figure 10. Vibration versus drop weight graph

Figs 9 and 10, shown the test of noise and vibration respectively, are plotted using the completed test data. According to the calculated average value, the best-fit curves are generated by built-in polynomial functions provided by MATLAB. The scattered original test data are also plotted onto the graph to investigate the overall trend and uncertainty.

Fig 11 shows a heat map of a vibration test on 75 kg dropped weights generated using MATLAB's built-in function. It will be used to analyse material deterioration in the following section.

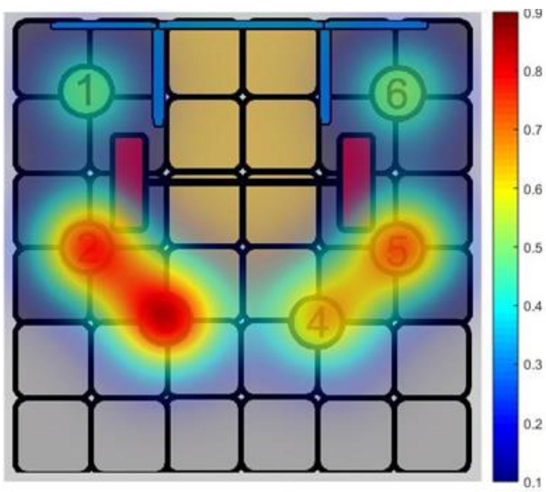


Figure 11. Vibration distribution heat map at 75 kg drop (the contour color represents the vibration amplitude in m/s^2)

6. Discussions

6.1 Relationship between drop weight and N&V

The overall results of both the noise and vibration tests show that the vibration intensity has a proportional relationship with increasingly heavy dropped weights. Noise tends to have a steadier trend than vibration. The vibration trend starts to increase significantly at the 50 kg point. In contrast, noise shows a stable curve until a minor drop at 70 kg.

6.2 Test uncertainty

By analysing the trend of the original data spots, the vibration tests showed significantly higher uncertainty than the noise tests. In Figs 9 and 10, the scattered black dots are distributed over a wide range. This also shows that the heavier the tested weight, the higher the uncertainty of the test.

6.3 Influence of barbell weight plate material

Tables 6 and 7 are summarized from a number of data sets (provided in Appendix A of the supplimentay material)**.**

Table 6 Noise test material comparison

Noise						
Combination	Weight (kg)	Average level (dB)	Combination	Weight (kg)	Average level (dB)	Percentage change
A	20.0	89	L	20.0	97	9.366%
B	25.0	91	M	25.0	97	7.404%

Table 7 Vibration test material comparison

Vibration						
Combination	Weight (kg)	Average level (m/s^2)	Combination	Weight (kg)	Average level (m/s^2)	Percentage change
A	20.0	0.151180	L	20.0	0.215338	42.438%
B	25.0	0.212567	M	25.0	0.273340	28.590%

Both tests show that the type of weight plate material highly influenced the result, especially in the vibration test. By considering the percentage change with different materials used, it can be seen that plastic-bumper plates are not considerably efficient at reducing noise and vibration with the specific floor material used in the gym of the University of Birmingham.

Nevertheless, in both Figs 9 and 10, because the type of weight plate was changed to rubber-covered weights after the 25 kg point, the gradient of the curve between the 20 and 25 kg tests is slightly higher than the overall curve of the rubber-covered plate, which could indicate that rubber covers on metal plates work effectively with the floor material.

6.4 The effectiveness of the floor material

Fig 9 shows that the curve tends to flatten after the 65 kg dropped weight, which could demonstrate rubber covers' high range of efficiency in reducing generated noise. In contrast, Fig 10 shows that the curve gets steeper after 50 kg dropped weight, which could be assumed the materials start to lose their ability to reduce vibration. However, these assumptions need to be verified by testing heavier dropped weights in the same scenario. This will be carried out in the future.

6.5 Material deterioration

According to the University of Birmingham News [20], the Sport & Fitness Centre opened on 22 May 2017, which means that material has been used for approximately 658 days before the tests. The detailed test date is provided in Appendix A of the supplimentay material. The data shows that there were several cracks on the surface of the material. Although the tests were done while avoiding dropping the weight onto the damaged part, there could be material deterioration under the surface beyond the visual area. By analysing the vibration data of the various device locations, the overall result shows that there is an imbalanced vibration detected throughout different locations. The majority of the tests show positions 2 and 3 carried relatively high vibration. This shows that the transferred vibration at positions 2 and 3 was significantly higher than the others. This could be due to the deterioration of materials underneath.

In addition, the overall values detected at positions 1 and 6 were relatively low and stable, which could be due to the heavy rigid barbell rig installed nearby. This shows that the rig could effectively contribute to reducing the vibration induced by gym activities.

6.6 Health and safety issues

An assessment published by the Health and Safety Executive [21] stated that regular exposure to loud noises above 85 dB can lead to permanent hearing loss or tinnitus. Furthermore, the Health and Safety Executive [22] also suggested several actions that can be taken to control noise. Similarly, with the reviews described earlier, it has also been proposed that the controls should be applied at the source of noise. Finally, ear plugs, screens, barriers, enclosures and absorbent materials could be used to reduce noise on its path to the people exposed.

6.7 Recommendations

6.7.1 Efficiency of material

According to the discussion on the effectiveness of the floor material, there was a particular high-efficiency working range for mitigating noise and vibration. Based on this investigation, a fitness centre could divide the barbell weight lifting area into regions with different restrictions on the heaviness of dropped weights and corresponding floor material. In addition, bumper and metal plates without rubber covers are not recommended for exercises in which weights are dropped. Regular checks or a replacement plan should be made for the floor material to avoid material deterioration.

6.7.2 Supplementary equipment

To further minimise noise and vibration, several types of equipment could be introduced throughout the fitness centre, such as absorbent ceilings, local screens, soundproof walls and vibration damping keels. In addition, for health and safety issues, the staff office/rest area should be located away from the noise sources and be built with suitably protective equipment. Note that the test results also show that the barbell rig could significantly reduce vibration; further connections between separate rigs could be introduced to enhance this capability.

6.7.3 Introduce mechanical damper system

A mechanical system could be introduced into the gym environment, such as floor vibration spring isolators and mounts provided by Inspired Noise UK. The spring system could possibly be installed underneath the weight-lifting area's floor material. Moreover, the hybrid isolated floor system introduced by Engle, Mahmoud and Chulahwat [23] could be applied into the floor design. This is according to the strategy of reducing vibration through its transmission path. However, these ideas need further verification, such as the equipment cost, construction duration, installation difficulties and necessities, etc.

6.7.4 Health and safety improvement

For health and safety assessments, the maximum permissible ambient noise has to be determined precisely. The measuring strategy for the fluctuation of noise over time could be used as a reference for noise and vibration monitoring scheme.

7.0 Conclusion

A concern on environmental noise and vibrations in the gym has been raised from the fact that there are more than 7,000 gyms in the UK and 1 in every 7 people in the UK is a member of a gym. This implies that fitness centres have become one of the most common spaces in mix-used buildings. On this ground, the study into noise and vibration induced by the gym activities is critical and necessary. This study has highlighted a field test conducted at the Fitness Centre at the University of Birmingham, UK. The study collects full range of smartphone sensors for estimation of several features of the tested materials obtained from various angles of noise and vibration sources. It is important to note that the ignorance of long-term noise in the work environment could be harmful to the human health (e.g. staff, users, public). Based on the rigorous measurements, a number of recommendations can be proposed for the Sport & Fitness Centre in the University of Birmingham to effectively minimise the induced noise and vibration.

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